Epitaxial Superconducting MgB$_2$ Thin Films by HPCVD

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Collaborators

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And
The groups of

Joan Redwing, Zi-Kui Liu, Darrell Schlom (PSU, Materials)

X. Q. Pan (U. Mich)
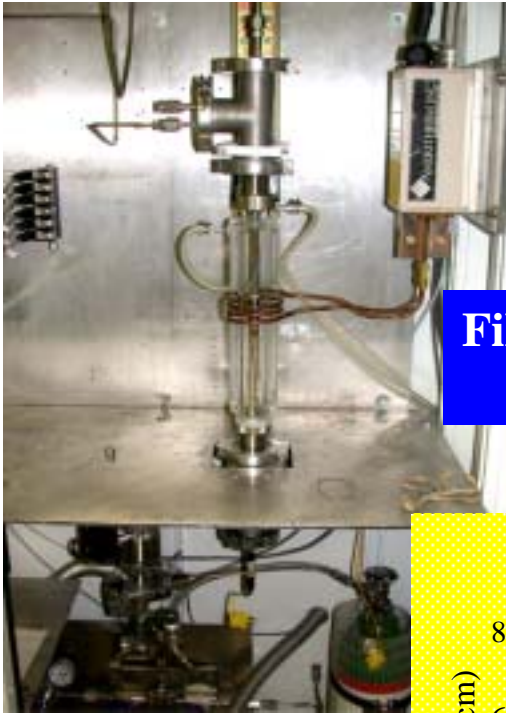**J. Schubert (FZ Jülich)**
Hans Christen (ORNL)
H. Hilgenkamp (Twente)
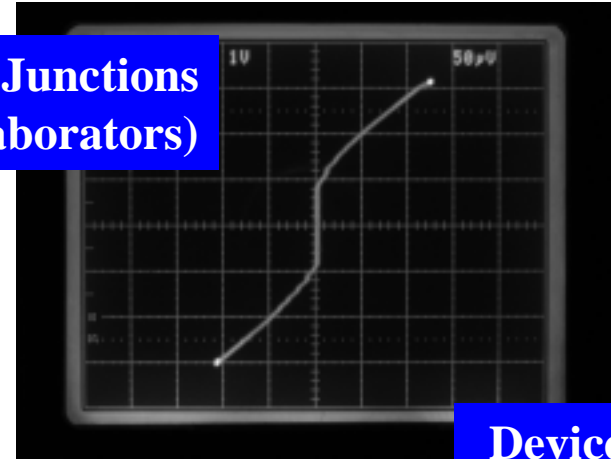
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College Park, MD

MgB$_2$ Films for Superconductor Electronics
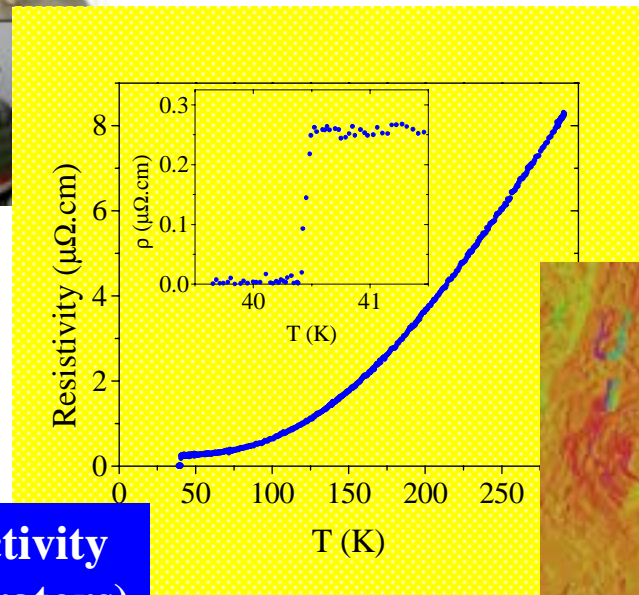

Film Deposition (PSU)

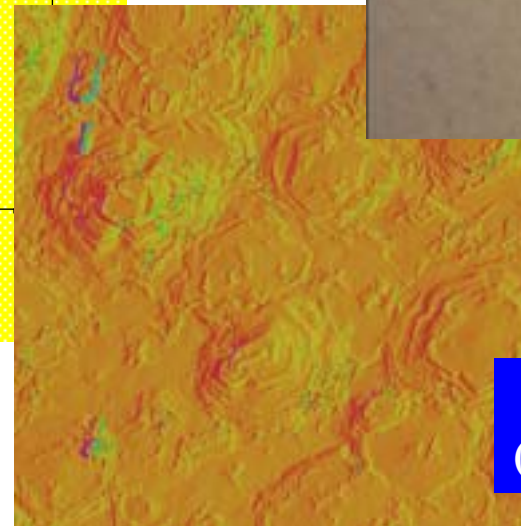**Josephson Junctions (PSU, collaborators)**

Device Fabrication (PSU, collaborators)

Superconductivity (PSU, collaborators)

Characterization (PSU, collaborators)
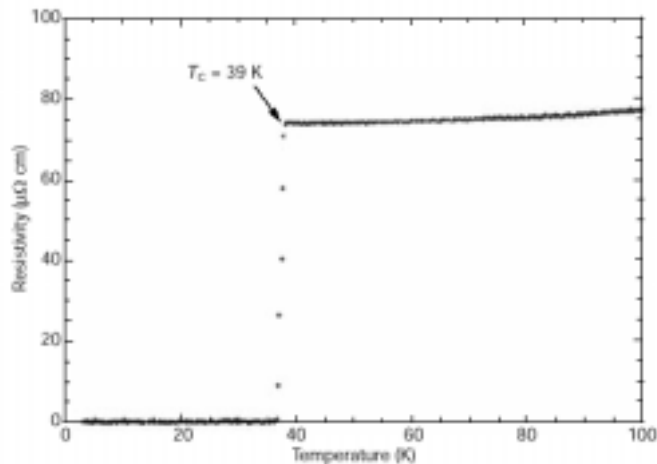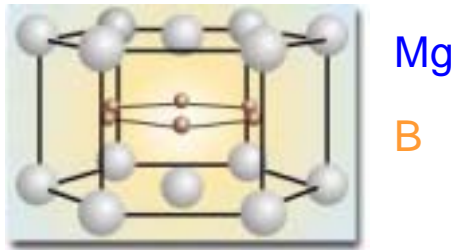
MgB$_2$ Superconductor

— T_c = 39 K

— Conventional, BCS-type with a coherence length ~ 5 nm

Mg

B

— B electron responsible

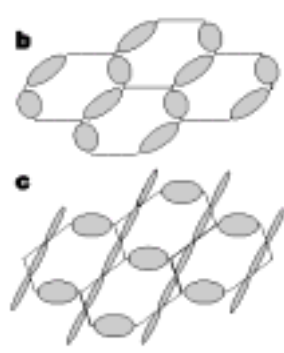— Multiband: σ bands and π band electrons each coupling with E$_{2g}$ phonon, giving rise to two energy bands:
  Δ(small) ~ 2 meV
  Δ(large) ~ 7 meV.

σ States

E$_{2g}$ Phonon

π State

Gaps vs. T

Nagamatsu *et al. Nature* 410, 63 (2001)
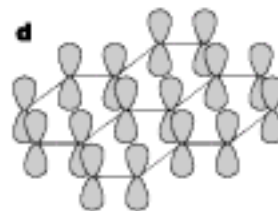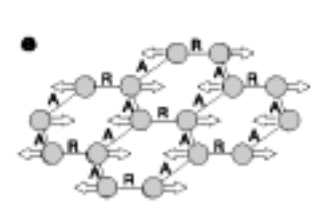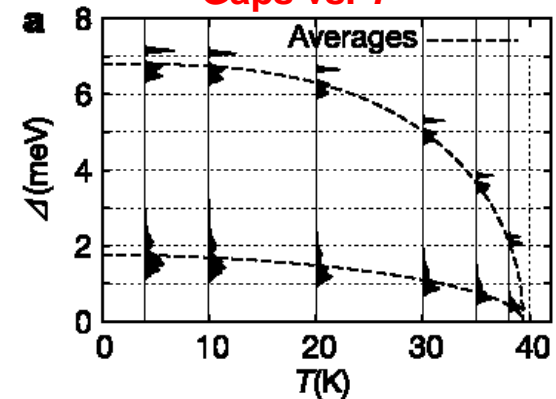
(Choi et al. *Nature* 418, 758 (2002))

Thermodynamics: Growth Window for Thin Films

Temperature (°C)

Process window: where the thermodynamically stable phases are **Gas+MgB$_2$**.

Mg partial pressure has to be high enough to keep MgB$_2$ phase stable

Mg pressure for the process window is very high for vacuum deposition technique at elevated temperatures.
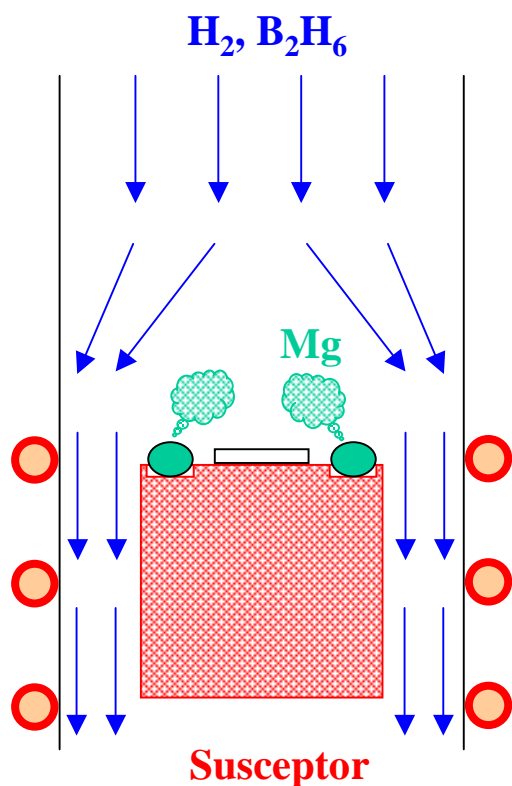
Mg flux to B flux ratio should be larger than 1:2

- Above 1:2, always results in MgB$_2$
- B flux determines growth rate
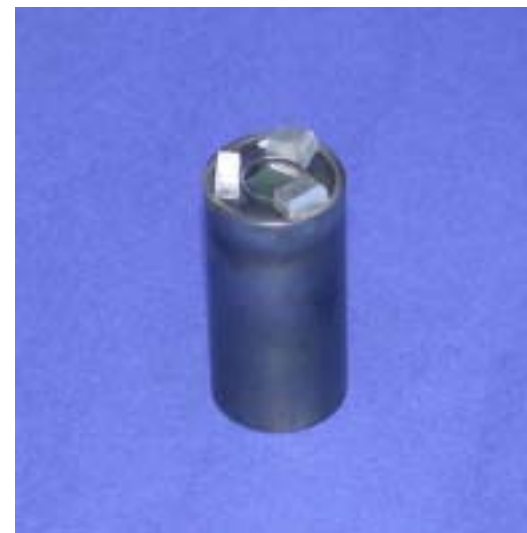- Below 1:2, MgB$_4$ or MgB$_7$ will occur

(Liu et al. APL 78, 3678 (2001))

Boundaries of the growth window:

$\log (P) = -7561/T + 8.673$ **(Upper)**

$\log (P) = -10142/T + 8.562$ **(Lower)**

Hybrid Physical-Chemical Vapor Deposition

Schematic View

H$_2$, B$_2$H$_6$
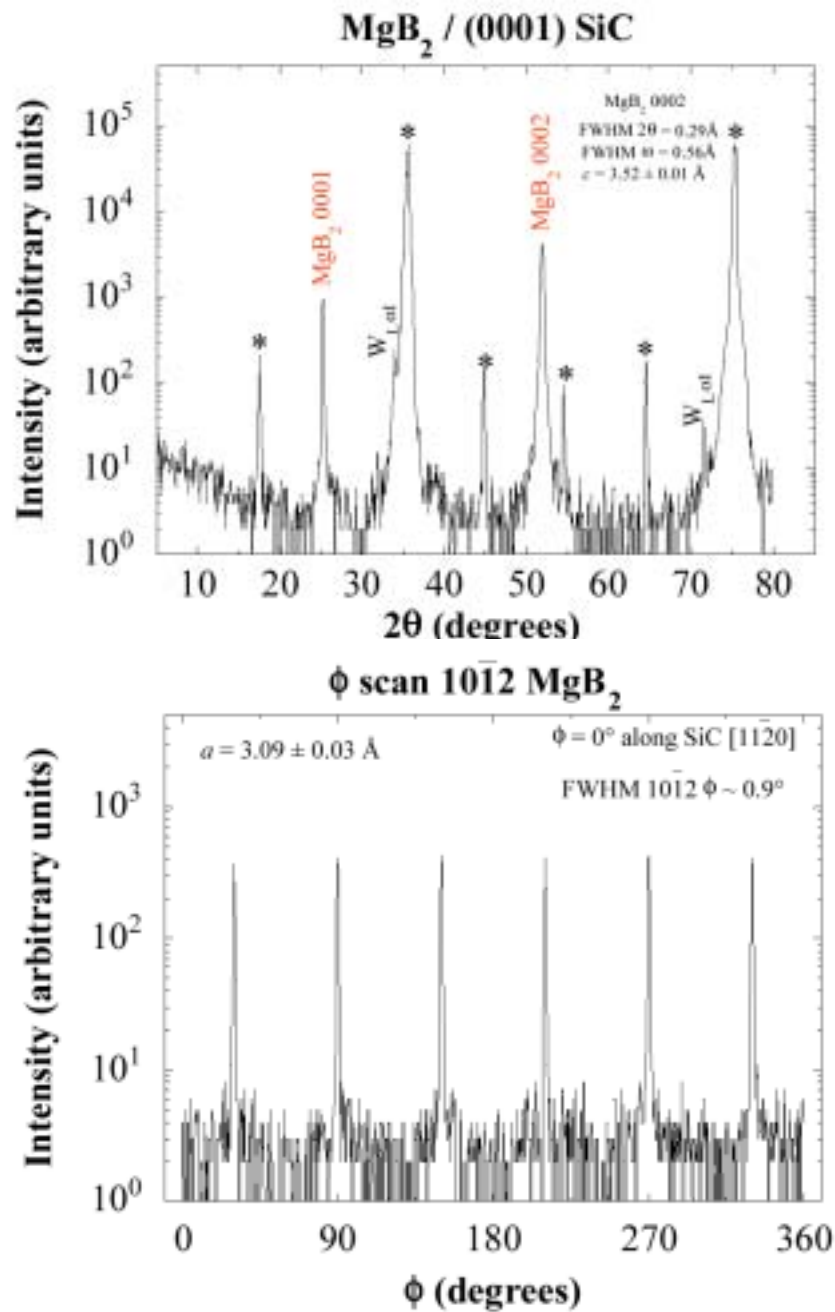
Mg

Susceptor

Deposition procedure and parameters:

• Purge with N$_2$, H$_2$

• Carrier gas: H$_2$

• P_{total} = 100 Torr.

• Heat susceptor to 700–760 °C. P_{Mg} = ? (44 mTorr is needed at 750 °C according to thermodynamics)

• Start flow of B$_2$H$_6$ mixture (1000 ppm in H$_2$): 25 - 250 sccm. Film starts to grow.

• Total flow: 1 slm

• Deposition rate: 1 - 18 Å/sec

• Switch off B$_2$H$_6$ flow, turn off heater.

Epitaxial Growth of MgB$_2$ Films

MgB$_2$ / (0001) SiC

MgB$_2$ 0002
FWHM 2θ = 0.29Å
FWHM ω = 0.56Å
c = 3.52 ± 0.01 Å

MgB$_2$ 0001

MgB$_2$ 0002

W$_{L\alpha1}$

Intensity (arbitrary units)

2θ (degrees)

φ scan 10$\bar{1}$2 MgB$_2$

a = 3.09 ± 0.03 Å

φ = 0° along SiC [11$\bar{2}$0]

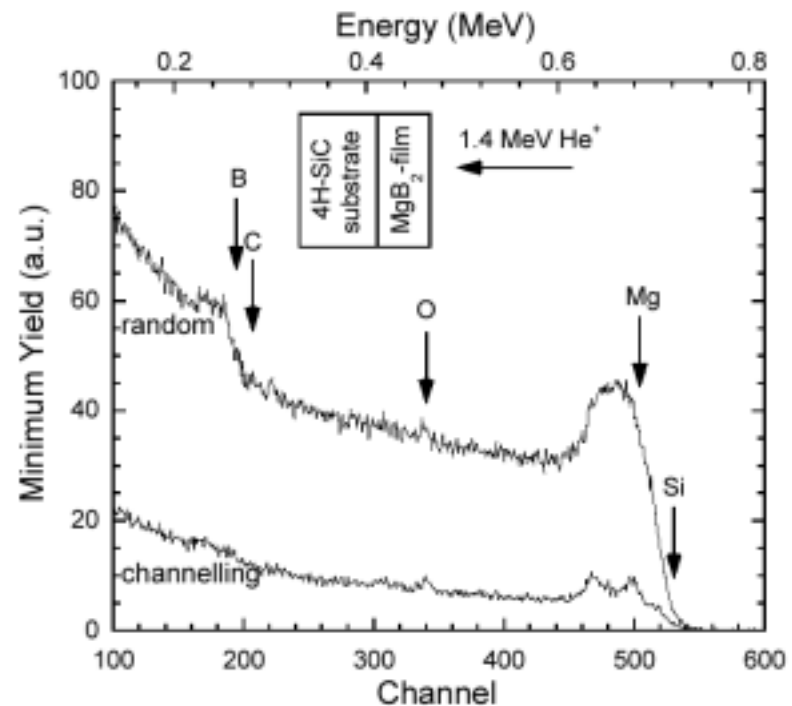FWHM 10$\bar{1}$2 φ ~ 0.9°

Intensity (arbitrary units)

φ (degrees)

X-ray diffraction
— *c* axis oriented, with sharp rocking curves
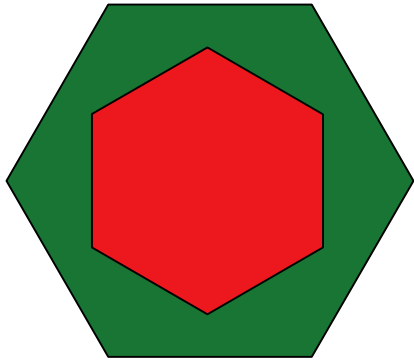— in-plane aligned with substrate, with sharp rocking curves
— free of MgO peaks

RBS and Channeling:
— Minimum channeling yield ~ 12%

Energy (MeV)

4H-SiC substrate

MgB$_2$-film

1.4 MeV He$^+$

B
C
random
O
Mg
Si
channelling

Minimum Yield (a.u.)

Channel

Epitaxial Growth on Sapphire and SiC

MgB_2/Al_2O_3 (0001)

MgB_2
a = 3.086 Å

Al_2O_3
a = 4.765 Å

4H-SiC
a = 3.07 Å

MgB_2/SiC (0001)

MgB$_2$

MgO Regions

No MgO

MgB$_2$

Al$_2$O$_3$

2 nm

6H-SiC
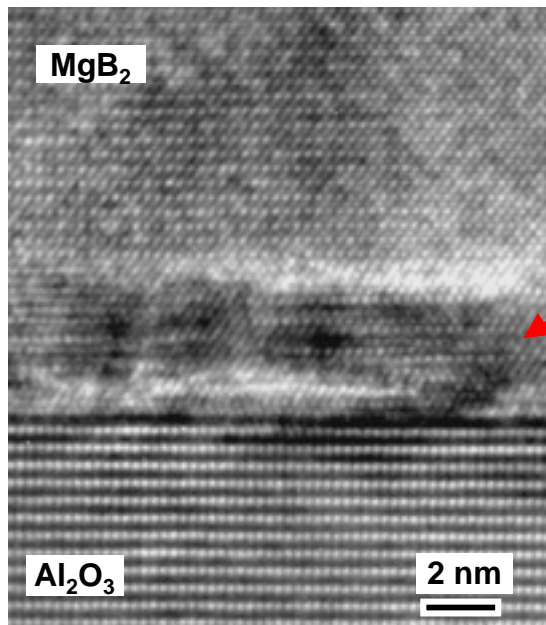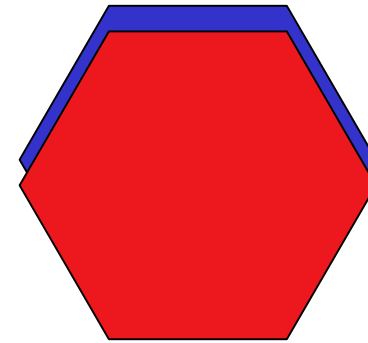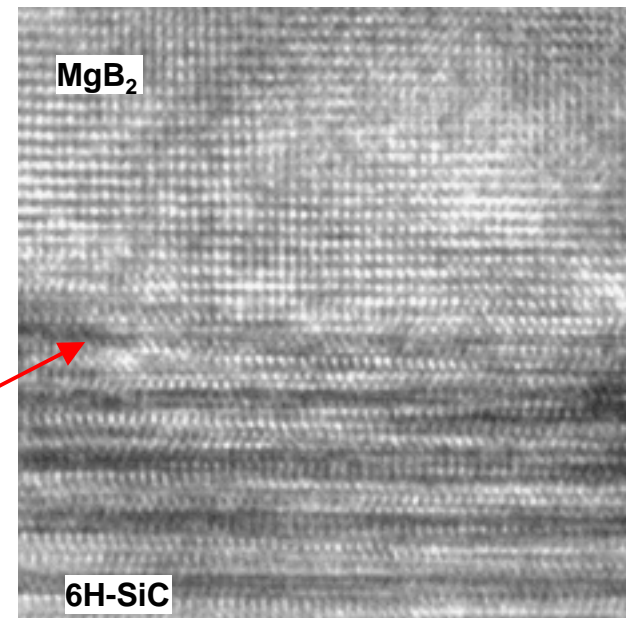
Superconducting Properties of MgB$_2$ Films
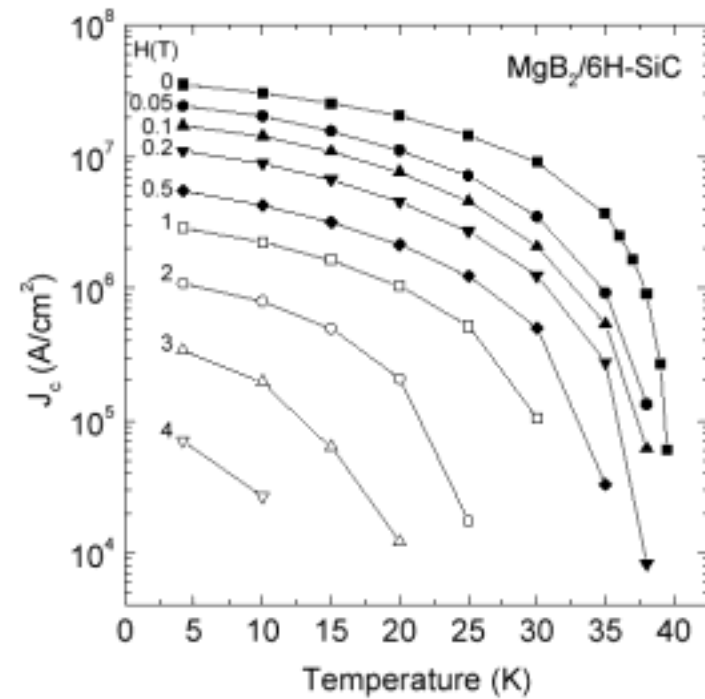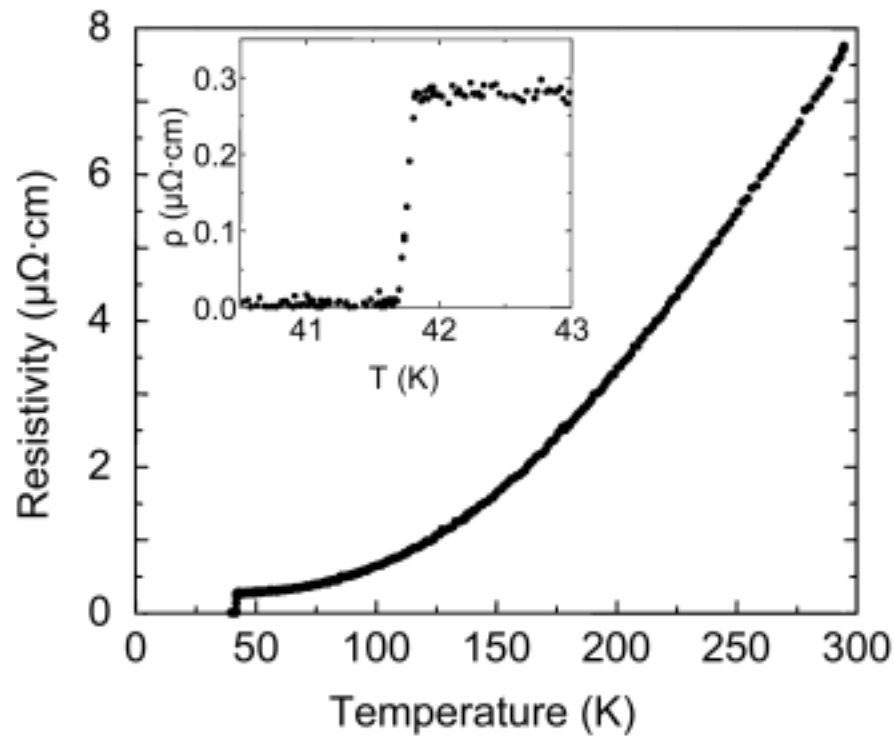
— High T_c: T_{c0} > 40 K
— Low resistivity: $\rho(50)$ ~ 0.26 μΩ·cm
— High Residual Resistance Ratio: RRR 30
— High J_c: $J_c(5K,0T)$ ~ 3.4 x 10^7 A/cm^2
— Magnetic field suppress J_c quickly due to lack of pinning centers.

Using v_F=4.8x10^7 cm/s, n=6.7x10^{22}/cm^3, the mean free path l ~ 900Å.

Different Thickness Dependences on SiC and Sapphire
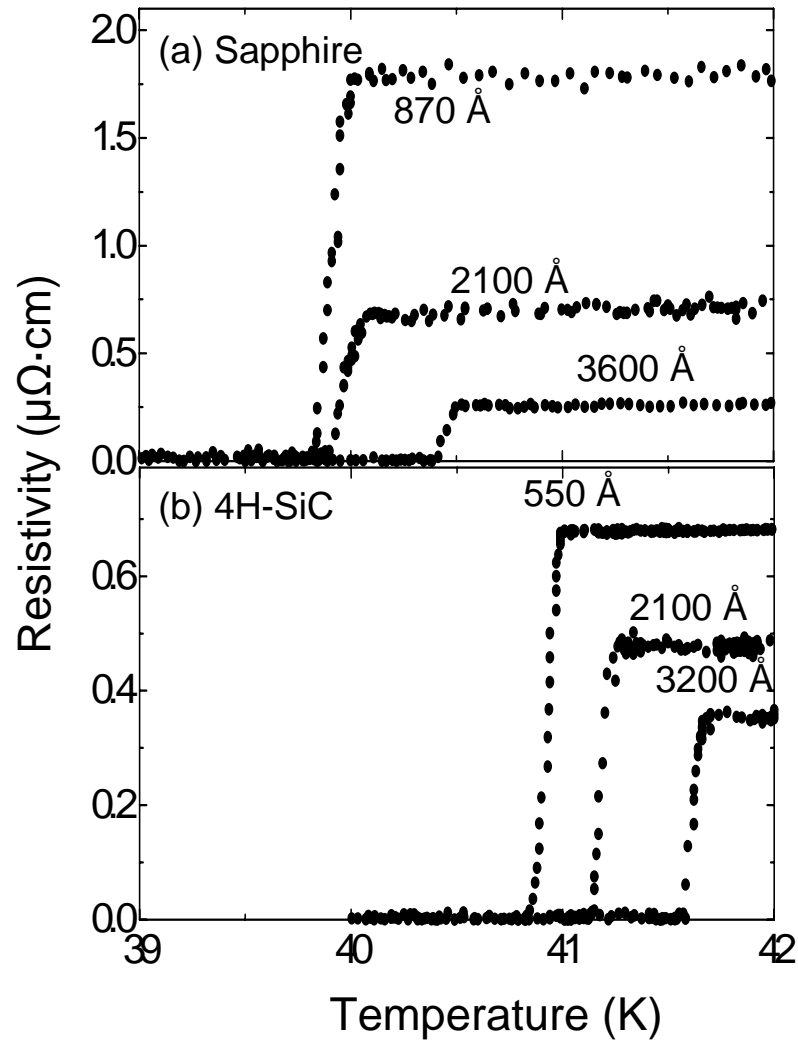
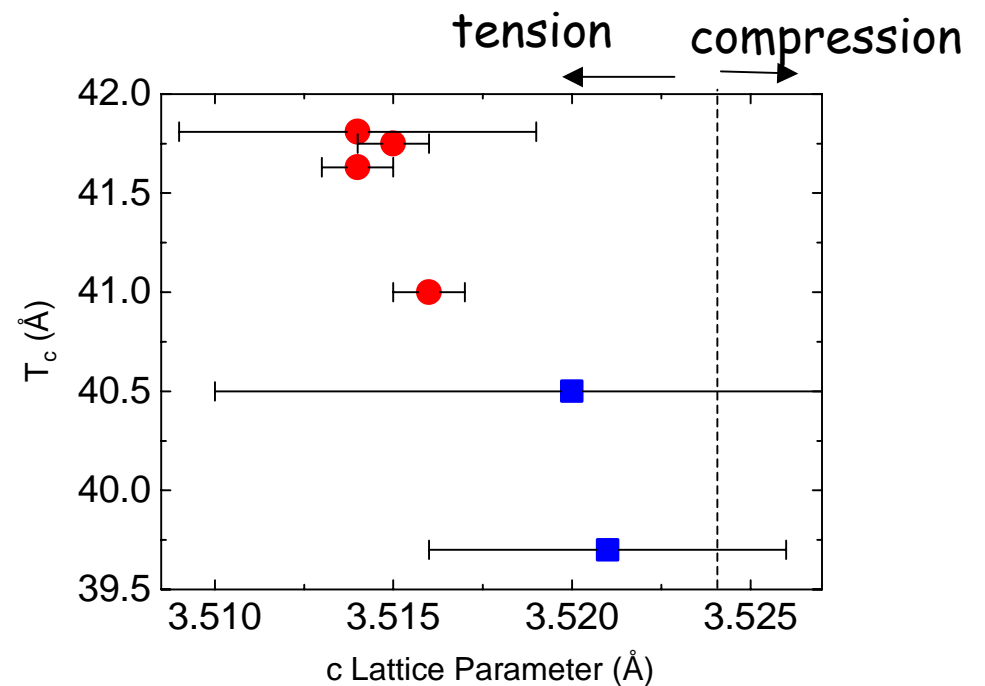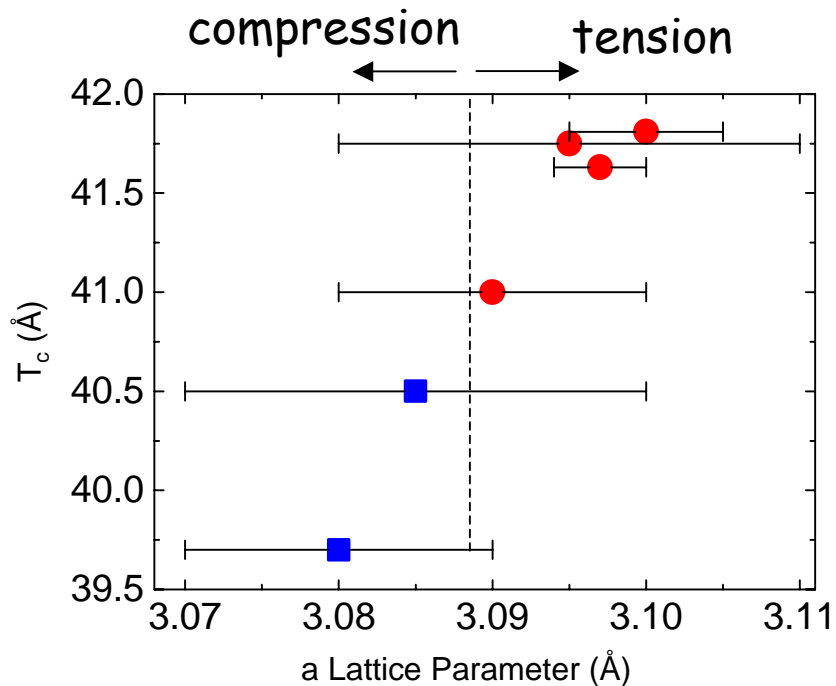— T_c increases with film thickness on both substrates

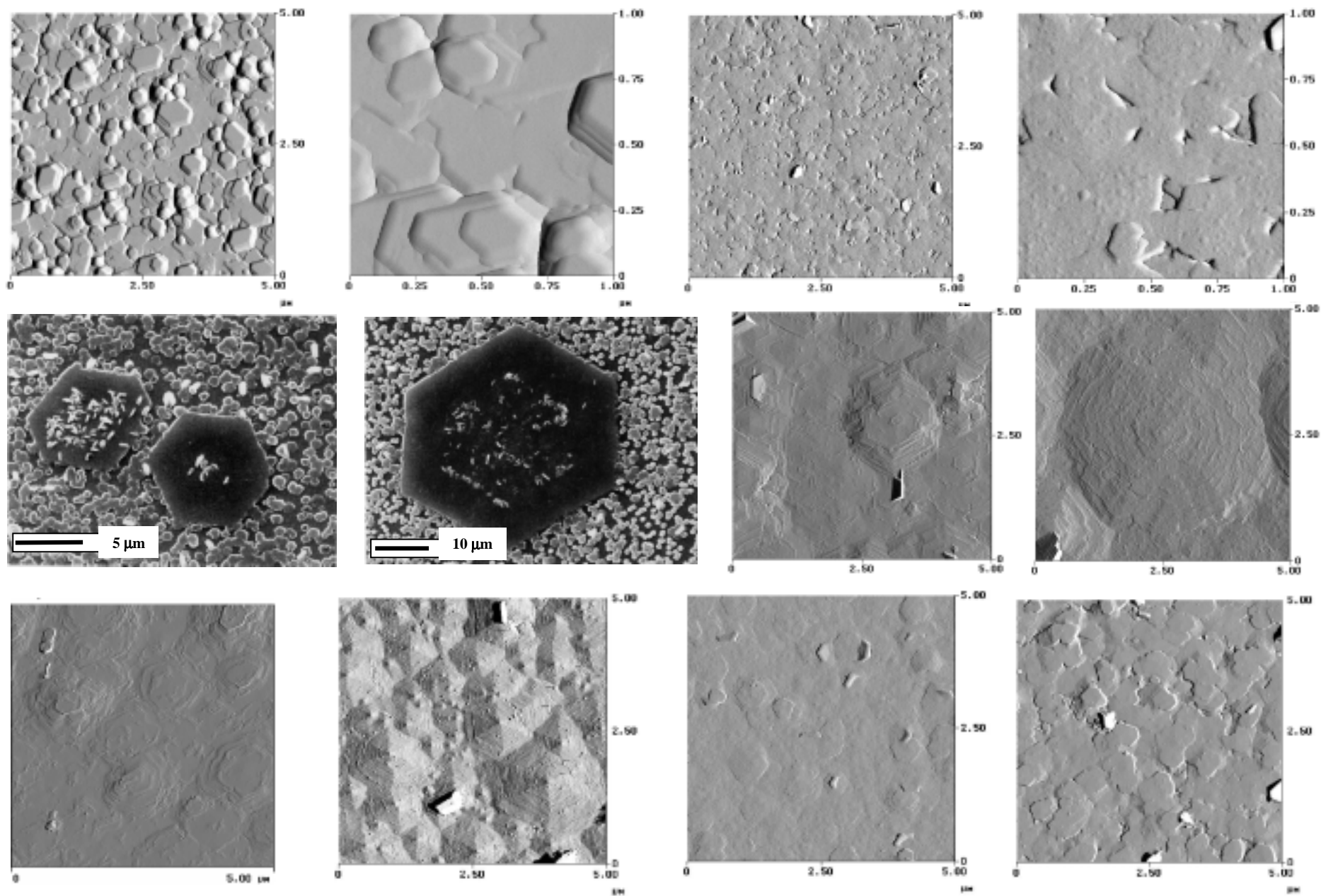— Films on SiC have higher T_c than those on sapphire.
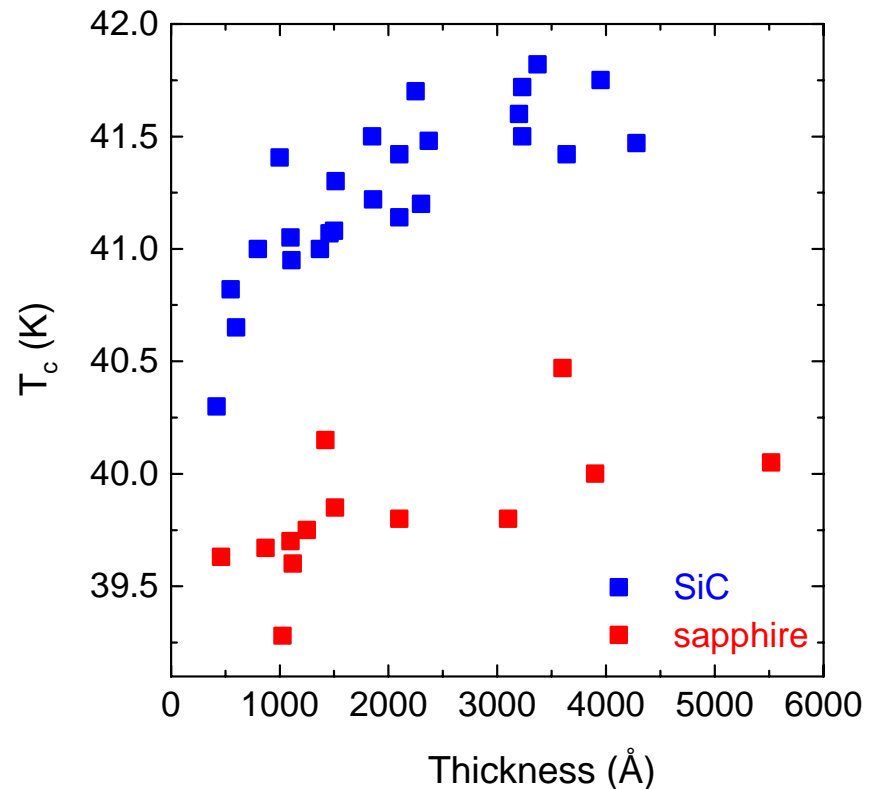
Correlation between Strain and T_c

— Dependences of T_c on strain the same for both substrates

— Higher T_c corresponds to larger tensile strain.

# Variations of MgB$_2$ Film Morphology

# Coalescence Tensile Strain: Increasing with Thickness

— Because the surface free energy of crystallites are larger than the free energy of grain boundaries, when crystallites are in close proximity, they spontaneously snap together to form grain boundaries. As a result, a tensile strain results from the crystallite coalescence.

— The tensile strain increases with increasing film thickness, until the film thickness is of the order of the grain size.

Can explain the tensile strain and its thickness dependence: due to the coalescence of MgB$_2$ growth columns.

before coalescence

after coalescence
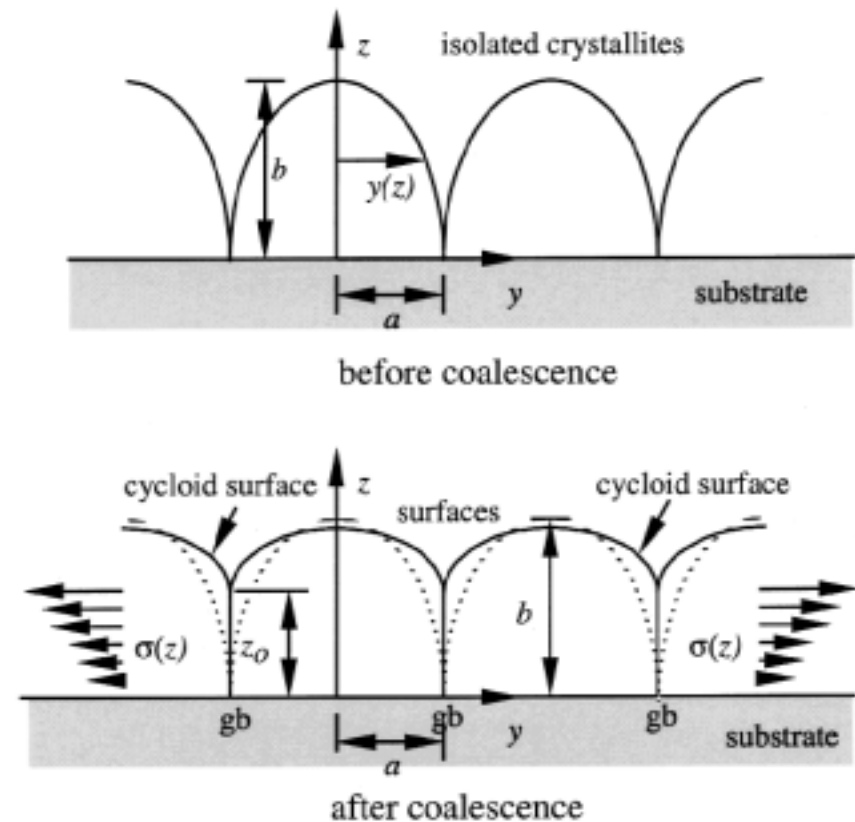
MgB₂ on TiB₂ and AlN Layers
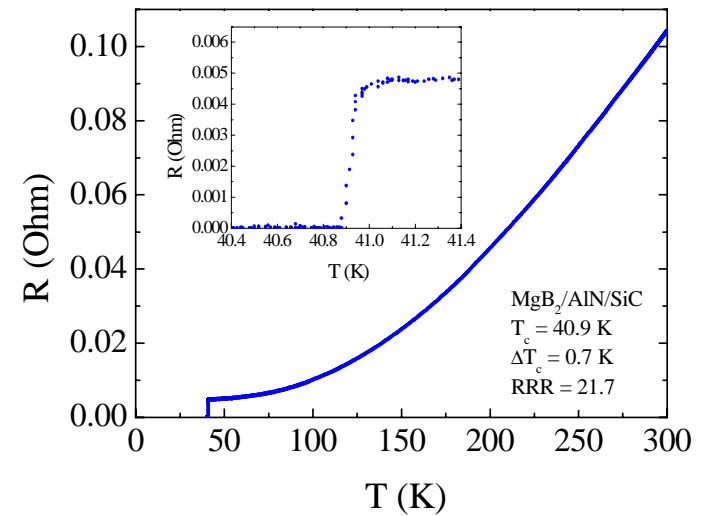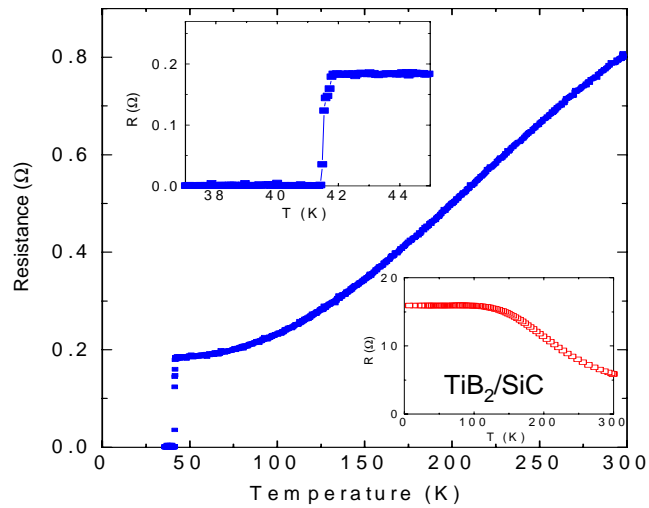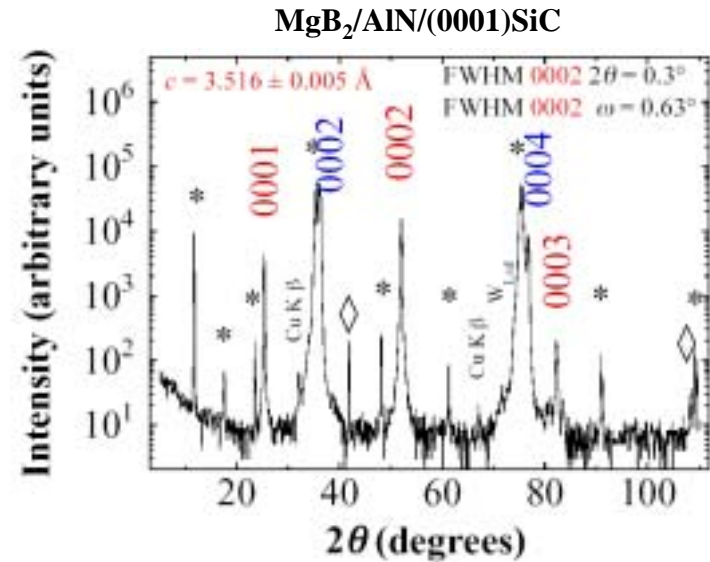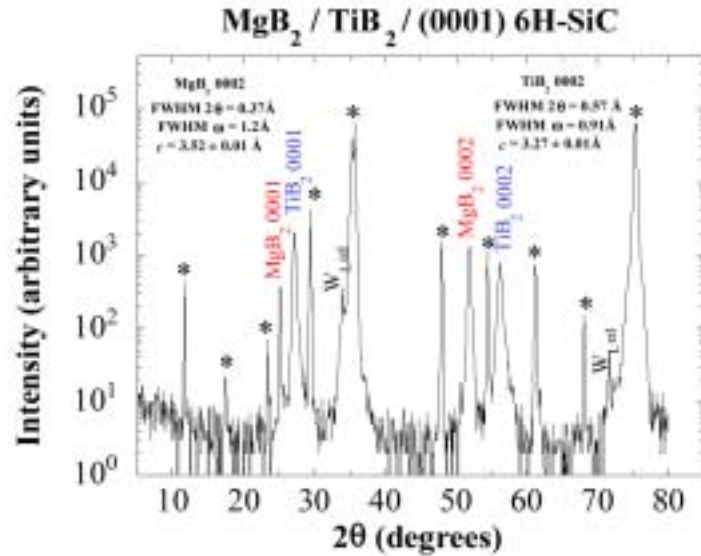
(TiB₂ provided by Hans Christen, Oak Ridge National Lab)

MgB$_2$ Nanobridge SQUID

D. Mijatovic, A. Brinkman, H. Hilgenkamp (Twente), A. Pogrebnyakov, S. Y. Xu

— Nanobridges: width ~ 170 nm, thickness 100 nm, and length 300 nm by focused ion beam.

— Critical current density : 5x10^7 A/cm^2.

— I-V characteristics hysteretic below 15 K, non-hysteretic above 15 K.

— The period of the voltage modulation corresponds to one flux quanta.

— Modulation observed at temperatures as high as 38.8 K
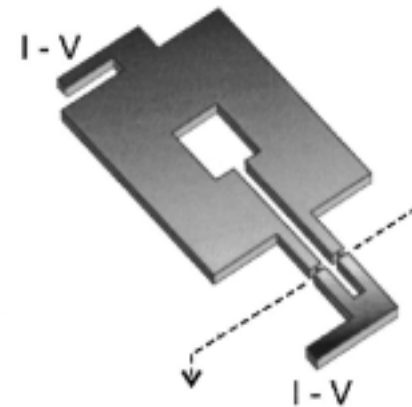
Voltage Modulation at 37 K
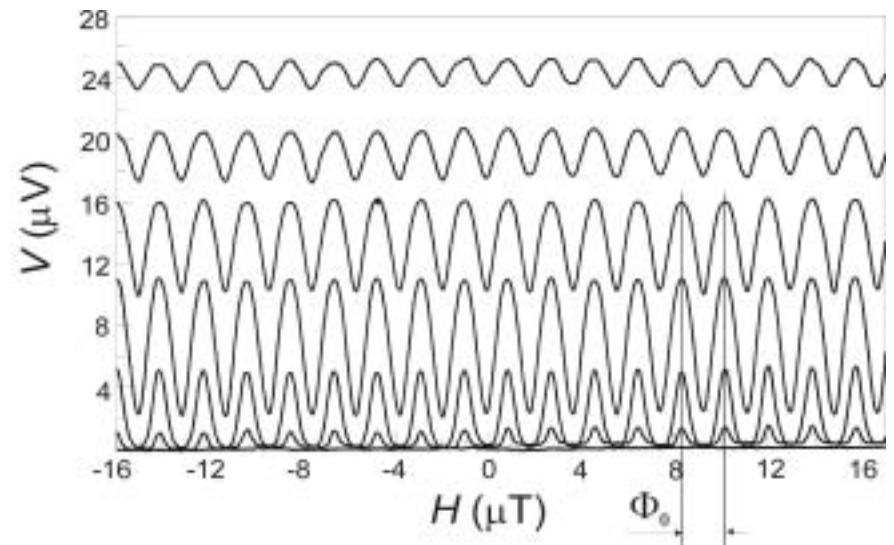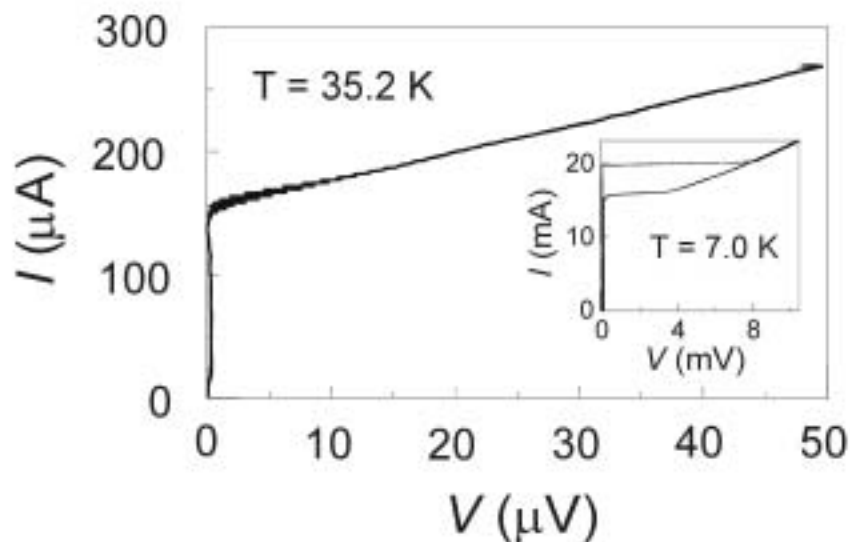
Conclusions

MgB_2 is a promising material for superconducting electronics.

The HPCVD technique successfully generates high Mg pressure and oxygen-free condition necessary for in situ growth of high quality MgB_2 films.

Epitaxial *in situ* MgB_2 films grown by HPCVD have very high T_c, J_c, and very low resistivity, indicative of intrinsic MgB_2 properties.

Films grow in hexagonal columns, which coalense as the film thickness increases. The coalescence tensile strain cause T_c to increase above the bulk value.

The HPCVD technique is promising for superconducting digital electronics using MgB_2.